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6. AUTHOR(S)
Richard Murray
John Doyle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
California Institute of Technology
Control & Dynamical Systems
1200 E. California Blvd.
Pasaadena, CA 91125

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Nonlinear Control Algorithms for Uninhabited Aerial Vehicles

AASERT Grant

Richard M. Murray John C. Doyle
Control and Dynamical Systems
California Institute of Technology
Pasadena, CA 91125

Final Report
1 April 1998 to 31 Mar 2001

1 Background and Objectives

This grant was an AASERT award that was part of the AFOSR PRET Center on Robust Nonlinear Control Theory with Applications to Aerospace Vehicles, which operated from 1995–2000. This AASERT award augmented the parent grant and was focused on developing nonlinear control algorithms for uninhabited aerial vehicles (UAVs).

The focus of the PRET center was fundamental research in general methods of analysis and design of complex uncertain nonlinear systems. We worked to create new mathematical theory as well as do the necessary work to make that theory help engineers solve a variety of real industrial problems. Caltech's Control and Dynamical Systems department (CITCDS) was created with precisely this goal, and our industrial collaborators, led by Honeywell, gave us a proven team. The University of Minnesota contributed valuable application and experimental expertise, and an academic team member geographically co-located with Honeywell, facilitating personnel exchange.

The original goal of this project was to develop software for nonlinear synthesis using numerical representations of systems, targeted at emerging applications in unmanned aerial vehicles (UAVs). As the project involved, this task broadened to consider general computational techniques in nonlinear control of both vehicle and fluid systems.

The main tasks that were addressed under this program were:

1. Development of theory and algorithms for model predictive control using control Lyapunov functions as a terminal constraint.
2. Development of modeling and control algorithms for large dimensional systems, including fluids and materials systems.

The ultimate goal of the research is to make these methods applicable to a wide class of realistic engineering systems, and easily accessible to control engineers.

2 Accomplishments

Due to the graduation of the initial student funded under this grant (Jim Primbs), several students received partial support from this award. The main accomplishments under this grant were:

- Development of the theory and preliminary algorithms for model predictive control using control Lyapunov functions as terminal constraints. This work was performed by Jim Primbs and Ali Jadbabaie [4, 5, 6].
- Implementation of control algorithms for control of a materials processing system for growth of superconducting thing films. This work was performed by Martha Gallivan, Lars Cremean and Melvin Flores [3, 1, 2].

Model Predictive Control

Two well known approaches to nonlinear control involve the use of control Lyapunov functions (CLFs) and receding horizon control (RHC), also known as model predictive control (MPC). The on-line Euler-Lagrange computation of receding horizon control is naturally viewed in terms of optimal control, whereas researchers in CLF methods have emphasized such notions as inverse optimality. We have focused on a CLF variation of Sontag's formula, which also results from a special choice of parameters in the so-called pointwise min-norm formulation. Viewed this way,

CLF methods have direct connections with the Hamilton-Jacobi-Bellman formulation of optimal control.

Building on these insights, we were able to develop a new approach to the stability analysis of finite receding horizon control applied to constrained linear systems. By relating the final predicted state to the current state through a bound on the terminal cost, it was shown that knowledge of upper and lower bounds for the finite horizon costs are sufficient to determine the stability of a receding horizon controller. This analysis is valid for receding horizon schemes with arbitrary positive-definite terminal weights, and does not rely on the use of stabilizing constraints. The result is a computable test for stability.

In addition, we have been able to show that for a sufficiently long horizon, a receding horizon policy will remain feasible and result in stability, even when no end constraint is imposed. In addition, offline finite horizon calculations can be used to determine not only a stabilizing horizon length, but guaranteed performance bounds for the receding horizon policy.

This work was the starting point for more applied work (as part of the DARPA Software Enabled Control [SEC] program) in optimization-based control of flight systems.

Modeling and Control of Materials Processing

The deposition of multi-species oxide thin films by chemical vapor deposition is an industrially-important but complex process. High wafer temperatures are required to obtain the desired gas phase and surface reactions, while the correct ratio of gas phase precursors must be maintained in the boundary layer above the wafer. Because film uniformity is critical in the performance of the final device, the temperature and precursor concentrations must be uniform across the entire wafer during deposition. Film properties are sensitive to slight disturbances in those process conditions, so sensors are also required for control.

We have designed and built a research reactor for the deposition of oxide thin films by metallorganic chemical vapor deposition. It has full field optical access for sensors, control capabilities, reaches temperatures up to 800°C, and maintains good uniformity over a 2" wafer. We have demonstrated its sensing capabilities with in-situ real-time measurements including Fourier-transform infrared spectroscopy, ultra-violet spectroscopy, and coherent gradient sensing. The benefits of this reactor are two-fold: to better understand the growth process and to improve the growth process by controlling process conditions and film properties.

For closed-loop control of thin film deposition, one would like to directly control film properties such as roughness, stress, or composition, rather than process parameters like temperatures and flow rates. This requires a model of the dynamic response of film properties to changes in process conditions. Direct atomistic simulation is far too slow to be used in this capacity, but a promising approach we explore here is to derive reduced-order dynamic models from atomistic simulations.

We have consider film growth on a vicinal surface using a kinetic Monte Carlo model. The temperature range spans the transition from smooth step flow to rough island growth. Proper Orthogonal Decomposition is used to extract the dominant spatial modes from the KMC simulations. Only five spatial modes adequately represent the roughness dynamics for all simulated times and temperatures, indicating that a 5-state model may be sufficient for real-time roughness control.

3 Personnel Supported

Jim Primbs, Caltech graduate student (1998–1999)
Ali Jadbabaie, Caltech graduate student (1999–2000)

Lars Cremean, Caltech graduate student (2000–2001)
Melvin Flores, Caltech graduate student (2000–2001)
Martha Gallivan, Caltech graduate student (2000–2001)

Two additional graduate students, Alex Fax and Jimmy Fung, received funding on this grant for a few months after the parent PRET grant ended (in June 2000).

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